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Generating mock data sets for large-scale Lyman- α forest correlation measurements

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Abstract. Massive spectroscopic surveys of high-redshift quasars yield large numbers of correlated Ly α absorption spectra that can be used to measure large-scale structure. Simulations of these surveys are required to accurately interpret the measurements of correlations and correct for systematic errors. An efficient method to generate mock realizations of Ly α forest surveys is presented which generates a field over the lines of sight to the survey sources only, instead of having to generate it over the entire three-dimensional volume of the survey. The method can be calibrated to reproduce the power spectrum and one-point distribution function of the transmitted flux fraction, as well as the redshift evolution of these quantities, and is easily used for modeling any survey systematic effects. We present an example of how these mock surveys are applied to predict the measurement errors in a survey with similar parameters as the BOSS quasar survey in SDSS-III.

Keywords: cosmology: large-scale structure — cosmology: spectroscopic surveys

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1 Introduction

The hydrogen Ly α absorption spectra of high-redshift sources are being revealed as an extremely powerful tool for the study of large-scale structure in observational cosmology. The numerous absorption features observed in the spectra of quasars usually described as the “Ly α forest” were originally interpreted as discrete gas clouds, but have been better understood and described as arising from the continuous cosmic web of filamentary structures that is expected in the Cold Dark Matter model of structure formation. Results from hydrodynamic cosmological simulations have shown that the observed properties of the Ly α forest are generally in good agreement with the hypothesis of a photoionized intergalactic medium with density fluctuations that are related to the same primordial perturbations that give rise to the galaxy distribution and the Cosmic Microwave Background fluctuations (e.g., [1, 2]). The Ly α forest spectra should therefore be considered as a continuous field of the Ly α transmitted fraction $F(\mathbf{x})$ (where \mathbf{x} is the redshift-space coordinate), which is related to the variations of the gas density, peculiar velocity and temperature along the line of sight, and eventually to the primordial density field, particularly on large scales, in which the complexities of non-linear evolution become less important.

In fact, if we have a large number of absorption spectra from different sources covering a large volume and with a sufficiently dense sampling, one can measure the redshift space power spectrum of the field $F(\mathbf{x})$. In the limit of large scales, this power spectrum should be related to the linear power spectrum of density perturbations as (see [3–5])

$$P_F(k, \mu_k) = b_\delta^2 (1 + \beta \mu_k^2)^2 P_L(k) , \quad (1.1)$$

where μ_k is the cosine of the angle of the wavevector \mathbf{k} in Fourier space relative to the line of sight, and P_L is the linear power spectrum of the mass density perturbations. This is the same form of the linear power spectrum derived by [6] for any class of observed objects with

a bias factor b_δ , which relates the amplitude of observed fluctuations to the amplitude of the underlying mass fluctuations. But for the Ly α forest, the redshift distortion parameter β depends on a second bias factor that is related to the response of the mean value of F to a large-scale peculiar velocity gradient, and must be determined independently.

Therefore, the promise of massive spectroscopic surveys of Ly α absorption spectra is to help determine the shape of $P_L(k)$ over a wide range of scales and redshifts, and to use this to obtain crucial cosmological measurements, such as the angular and redshift scale of the Baryon Acoustic Oscillations, or the effect of neutrinos on the power spectrum (e.g., [7]). In addition, one can determine the values of b_δ and β at each redshift, which are in principle predictable with hydrodynamic simulations from the small-scale physics that determine the properties of the Ly α forest ([5]). A first step in this direction was recently accomplished by [8] from the first analysis of the quasar absorption spectra in the BOSS survey.

Accurately measuring the power spectrum requires a careful evaluation and correction of any systematic errors that may be present in this measurement in the analysis of real data. The only way to reliably doing this is by generating several random realizations of the multiple Ly α absorption spectra in a survey, and introducing into them any possible systematic effects to see how they may impact the inferred power spectrum in the end. Some of the systematic effects that need to be considered are the following: errors in the modeling of the quasar continuum $C(\lambda)$, which is needed to evaluate the transmitted fraction from the observed flux, $f(\lambda) = C(\lambda)F(\lambda)$; variable spectral resolution and noise; flux calibration errors; the impact of the redshift evolution of the Ly α forest; the presence of damped Ly α , Lyman limit systems and metal absorption lines in the spectra; or variations in the intensity of the cosmic ionizing background. Modeling these systematic effects as accurately and reliably as possible requires our ability to generate mock surveys of Ly α absorption spectra in large numbers, for many different cases, and in a way that can be easily used. These mock surveys must include a large number of lines-of-sight over large volumes (like the ongoing BOSS survey in SDSS-III; [9]), and somehow include the small-scale fluctuations of the Ly α forest that are present in the observed spectra of sources that are point-like for practical purposes.

Generating these mock surveys directly from three-dimensional simulations, by selecting lines of sight from them, presents several difficult challenges. The first is that having a large enough volume to correctly simulate the power spectrum, at least up to scales as large as the BAO peak, implies that the resolution of the simulations cannot capture the smallest relevant scales for the Ly α forest. In addition, when using large three-dimensional simulations, the computer resources that are required may not allow obtaining many mocks that are independent, or changing the parameters of these mocks in an efficient and fast way to enable a large number of tests.

This paper presents a method to efficiently create these mock surveys of Ly α absorption spectra, taking advantage of the fact that the transmitted fraction F needs to be generated only on the discrete lines of sight to the survey sources. The method consists of generating one-dimensional fields for each line of sight and introducing correlations among them as if they had been drawn from a three-dimensional field. The capacity that is lost with this method is using hydrodynamic simulations that include the non-linear gravitational evolution of density fluctuations and other physical effects to simulate the field $F(\mathbf{x})$. However, if we care only about the large-scale power spectrum of this field and the errors to which it can be measured, it is in principle enough to ensure that the mocks have the same variance in the small-scale fluctuations to reproduce their effect on large scales. The way the mock surveys

are generated is by using an input power spectrum of $F(\mathbf{x})$ in redshift space that includes a non-linear correction for small scales, and which is assumed to be calibrated from the results of cosmological simulations with enough resolution or directly from the observational results. The mocks can also incorporate any desired one-point distribution of F and the redshift evolution of both the power spectrum and the distribution of F .

Hence, the philosophy of these mock surveys is that they are generated from an input model of the power spectrum and other quantities, and that they should be used for predicting the large-scale correlation measurements of the Ly α forest and the way they are affected by any systematic errors that can be introduced. However, the field $F(\mathbf{x})$ that is simulated is purely local and inferred from the linear overdensity, so it does not reproduce the 3-point or higher n-point correlations of the Ly α forest.

The method is presented in detail in §2, and an application to an example of a survey similar to BOSS is presented in §3. Another application of these mocks to simulate the effect of damped Ly α systems is discussed in [10]. This method was already used for simulating the sample of spectra used in [8], and is being improved for application to the final BOSS survey.

A standard flat Λ CDM cosmology is used in this paper with the following parameters: $h = 0.72$, $\Omega_m = 0.281$, $\sigma_8 = 0.85$, $n_s = 0.963$, $\Omega_b = 0.0462$.

2 Method to generate mocks of correlated Ly α spectra

A Ly α forest spectrum is given by the fraction of transmitted flux, $F = \exp(-\tau)$, where τ is the optical depth, at each observed wavelength. We define the comoving coordinate in redshift space, x , related to the wavelength by $dx = c/H(z)(d\lambda/\lambda_\alpha)$, where $H(z)$ is the Hubble constant, the redshift is $1 + z = \lambda/\lambda_\alpha$ and $\lambda_\alpha = 1216 \text{ \AA}$ is the Ly α resonance wavelength. The observed spectrum is the product of $F(x)$ times the continuum of the source, which is not independently observed and must be modeled. We shall not deal in this paper with the issue of modeling the continuum. Our mocks are realizations of the function $F(x)$ on multiple, correlated lines of sight.

In this paper we shall generally work with the variable

$$\delta_F(x) = \frac{F(x)}{\bar{F}} - 1, \quad (2.1)$$

where \bar{F} is the mean value of F at a given redshift. All the 2-point correlations appearing in this article are of this δ_F variable unless otherwise stated. This section describes the method to generate a set of mock Ly α spectra with any specified distribution function and power spectrum for the δ_F variable. The main idea for the case of a Gaussian field is explained in 2.1, which is then generalized to any desired distribution of δ_F (2.2). The inclusion of redshift evolution is discussed in 2.3.

2.1 Generation of a Gaussian random field

The most important requirement that our mock Ly α spectra must meet if they are to accurately predict any systematic and statistical errors in the measurements of large-scale correlations in δ_F is that they have a redshift space power spectrum of the flux that accurately matches the observed one. In this way, the intrinsic variance of the Ly α absorption at any scale can be reproduced, and the way it affects the sampling errors on all other scales is correctly taken into account. Our method to generate mock Ly α spectra can take as input

any desired power spectrum $P_F(k_{\parallel}, k_{\perp})$ in redshift space, where k_{\parallel} , k_{\perp} are the components of the wave vector in Fourier space parallel and perpendicular to the direction of the line of sight.

2.1.1 Sampling the volume unevenly

The usual way to generate a Gaussian random field in realizations of cosmological perturbations is to generate first a set of independent Fourier modes in a three-dimensional cubic box with a specified power spectrum, and then doing the Fourier transform to obtain the real-space field. This method yields the value of the field at all the cells in the cubic volume at once.

However, to simulate the measurement of correlations up to the BAO scale in a survey of quasar spectra, we need to cover a volume with a size of at least several times the BAO scale, with a required resolution needed to capture the fluctuations in the low-density intergalactic medium of at least $\lambda_J/(2\pi) = \sqrt{3/2} c_s t$, or ~ 100 comoving kpc (where λ_J is the Jeans length, c_s is the sound speed of the intergalactic gas, and t the age of the universe; well-resolved simulations of the IGM typically use cells a factor of a few smaller than the Jeans length; see, e.g., [11, 12]). The minimum dynamic range from the smallest to the largest scale is then $\sim 10^4$, or 10^{12} simulated points (and even larger if the entire volume of a survey like BOSS is to be generated), which results in a serious computational problem for being able to easily generate large numbers of mocks in a simple way.

Our method uses the fact that we are only interested in the values of the field along a number of infinitely thin lines of sight traced by the quasar light. Hence, we can generate a Gaussian field on these one-dimensional lines only, and introduce correlations among them directly in real space. A first, simple-minded way to achieve this might be to first generate an independent Gaussian variable at each pixel, g_i , and then combine them to generate the final field $\delta_{gj} = L_{ij}g_i$ which has the desired correlation C_{ij} :

$$C_{ij} = \langle \delta_{gi} \delta_{gj} \rangle = \langle L_{ik} g_k L_{jl} g_l \rangle = L_{ik} L_{jl} \delta_{kl} = L_{ik} L_{jk} . \quad (2.2)$$

A particularly efficient way to obtain the required matrix L for the transformation is the result of the Cholesky decomposition of the covariance matrix C , i.e., a lower triangular matrix L obeying $C = LL^T$. Numerically, there are several algebraic packages that perform the Cholesky decomposition very efficiently.

For a practical application, the number of pixels that are needed to model a typical observed spectrum and to include the power down to the smallest relevant scales is $N_p \sim 10^3$ for each line of sight. For a survey with N_q quasars, the total number of elements of the correlation matrix C that need to be computed is $(N_p \times N_q)^2$. Clearly, this method would break down for a relatively small number of quasars. Fortunately, there is a better way to do it.

2.1.2 Parallel lines of sight

Let us assume for the moment that the lines of sight in the survey are perfectly parallel. Let $\delta_g(x_{\parallel}, \mathbf{x}_{\perp})$ be the correlated Gaussian variable we want to generate at the position x_{\parallel} of the line of sight at coordinate \mathbf{x}_{\perp} . We can do the one-dimensional Fourier transform of δ_g on the direction of the line of sight only, to obtain $\tilde{\delta}_g(k_{\parallel}, \mathbf{x}_{\perp})$. These one-dimensional Fourier modes have the following correlation:

$$\langle \tilde{\delta}_g(k_{\parallel}, \mathbf{x}_{\perp}) \tilde{\delta}_g(k'_{\parallel}, \mathbf{x}'_{\perp}) \rangle = \frac{1}{2\pi} \int d\mathbf{k}_{\perp} \exp(i\mathbf{k}_{\perp} \cdot \mathbf{x}_{\perp}) \int d\mathbf{k}'_{\perp} \exp(i\mathbf{k}'_{\perp} \cdot \mathbf{x}'_{\perp}) \quad (2.3)$$

$$\begin{aligned}
& \times \delta^D(k_{\parallel} + k'_{\parallel}) \delta^D(\mathbf{k}_{\perp} + \mathbf{k}'_{\perp}) P(\mathbf{k}) \\
& = 2\pi \delta^D(k_{\parallel} + k'_{\parallel}) P_{\times}(k_{\parallel}, |\mathbf{x}_{\perp} - \mathbf{x}'_{\perp}|) ,
\end{aligned}$$

where the symbol δ^D stands for the Dirac delta function, $P(\mathbf{k})$ is the power spectrum of δ_g , and

$$P_{\times}(k_{\parallel}, r_{\perp}) = \frac{1}{2\pi} \int_{k_{\parallel}}^{\infty} k dk J_0(k_{\perp} r_{\perp}) P(k_{\parallel}, k_{\perp}) . \quad (2.4)$$

The crucial property is that the one-dimensional modes $\tilde{\delta}_g$ on different lines of sight are independent except when $k_{\parallel} = k'_{\parallel}$. Therefore, the problem is now separated for each value of k_{\parallel} , and the Cholesky decomposition operation needs to be performed on N_p matrices of size $N_q \times N_q$ only.

Hence, the procedure to be followed in our method is as follows. We first choose a grid of values of k_{\parallel} for the Fourier transforms on the line of sight. For each value of k_{\parallel} , we compute the correlation of the one-dimensional Fourier modes for every pair of lines of sight, using equations (2.3) and (2.4). Each one of these $N_q \times N_q$ matrices, $C_k = P_{\times}(k_{\parallel}, r_{\perp})$, is then Cholesky-decomposed to obtain a matrix L_k . After generating a set of independent Gaussian variables for each quasar and each value of k_{\parallel} , g_{kq} , we compute the new set $\tilde{\delta}_g = L_k g$, and we then do the inverse one-dimensional Fourier transform of these to finally obtain the δ_g variables, with all the real space correlations that are implied by the input 3-d power spectrum $P(\mathbf{k})$.

In reality, the Ly α spectra need to be generated for quasars that are at different redshifts. We do this by first generating the spectra lines of sight of a long enough comoving length L , evaluating δ_g on bins of comoving width Δx . We set the center of the line of sight at a central redshift z_c (we use $z_c = 2.6$ in this paper), and every bin is then mapped into a redshift according to its comoving coordinate. We then use only the part of the spectrum of each quasar that is in the restframe wavelength range for Ly α forest analyses. We use $1041 \text{ \AA} < \lambda_r < 1185 \text{ \AA}$ in this paper, the usual range to avoid Ly β contamination and the proximity effect zone near the quasar. We also use $L = 4096 h^{-1} \text{ Mpc}$, long enough to make any periodicity effects negligible, and $\Delta x = 0.5 h^{-1} \text{ Mpc}$, slightly smaller than the typical pixel width in the BOSS spectrograph ($1 \text{ \AA} \simeq 0.7 h^{-1} \text{ Mpc}$ at the redshifts of interest).

2.2 Flux distribution

The principal goal of the mocks of correlated Ly α forest spectra we want to generate is to simulate the observed spectra in a survey like BOSS that includes all of the statistical and systematic errors we may consider to obtain a correction for them when computing any statistical property. It is therefore important that the perturbation in the transmitted flux fraction, δ_F , in the mock spectra has the same distribution as the observed one, in order that the impact of continuum fitting and noise on the measured correlations and their errorbars are correctly simulated. Note that the value of the noise that is added in the mocks and the way that the continuum fitting is obtained will depend on a complex way on the values of δ_F . Here we generalize our method to generate a field δ_F with the desired probability distribution function $p_F(\delta_F)$ and any power spectrum $P_F(\mathbf{k})$. Although the higher order n-point correlations of F will obviously still be different for the mocks and the real Ly α forest spectra, we expect this to have negligible impact on the computed errors of any statistical measurements on large scales (e.g., [2] found that errors computed as if the flux field was

Gaussian were close to errors determined by bootstrapping over real spectra, even on Mpc scales).

This generalized method consists of generating first our field δ_g with a Gaussian distribution, $p_g(\delta_g) = \exp(-\delta_g^2/2)/\sqrt{2\pi}$, with a different power spectrum P_g such that, after transforming the field to the new variable $\delta_F(\delta_g)$, the desired probability distribution function $p_F(\delta_F)$ and power spectrum P_F are obtained. The required transformation $\delta_F(\delta_g)$ is obtained by integration of the equation

$$\frac{d\delta_F}{d\delta_g} = \frac{p_g(\delta_g)}{p_F(\delta_F)} . \quad (2.5)$$

Let us consider the correlation functions $\xi_F(r_{12})$ and $\xi_g(r_{12})$ of the field values at two points \mathbf{x}_1 and \mathbf{x}_2 separated by the distance r_{12} . We designate these field values as δ_{F1} , δ_{F2} , δ_{g1} , δ_{g2} . Since the field δ_g is strictly Gaussian, the correlation functions are related by

$$\begin{aligned} \xi_F(r_{12}) &= \langle \delta_{F1} \delta_{F2} \rangle \\ &= \int_{-1}^{1/\bar{F}-1} d\delta_{F1} \int_{-1}^{1/\bar{F}-1} d\delta_{F2} p_{2F}(\delta_{F1}, \delta_{F2}) \delta_{F1} \delta_{F2} \\ &= \int_{-\infty}^{\infty} d\delta_{g1} \int_{-\infty}^{\infty} d\delta_{g2} p_{2g}(\delta_{g1}, \delta_{g2}) \delta_{F1} \delta_{F2} \\ &= \int_{-\infty}^{\infty} d\delta_{g1} \int_{-\infty}^{\infty} d\delta_{g2} \frac{\exp \left[-\frac{\delta_{g1}^2 + \delta_{g2}^2 - 2\delta_{g1} \delta_{g2} \xi_g(r_{12})}{2(1 - \xi_g^2(r_{12}))} \right]}{2\pi \sqrt{1 - \xi_g^2(r_{12})}} \delta_F(\delta_{g1}) \delta_F(\delta_{g2}) . \end{aligned} \quad (2.6)$$

Note that we have assumed that the Gaussian field has unit variance, without loss of generality as an overall normalization factor can always be included in the definition of the mapping $\delta_F(\delta_g)$. This relation between the two correlations ξ_F and ξ_g is actually a one-dimensional function that is totally independent of the separation r_{12} or any other variable: it depends only on the relation $\delta_F(\delta_g)$. We can therefore tabulate and invert the function $\xi_F(\xi_g)$.

The procedure to generate a random field δ_F is therefore the following: we start with an input model for the three-dimensional power spectrum P_F of the flux transmission, and compute the Fourier transform to obtain ξ_F . We then convert this to the correlation function ξ_g , and proceed to compute the correlations of one-dimensional power for the Gaussian field g in equation 2.4), which can be re-expressed as:

$$P_{g\times}(k_{\parallel}, r_{\perp}) = \int_{-\infty}^{\infty} dr_{\parallel} e^{ik_{\parallel} r_{\parallel}} \xi_g(r_{\parallel}, r_{\perp}) . \quad (2.7)$$

We mention here that this procedure does not in general work for any distribution function $p_F(\delta_F)$, because sometimes the resulting power $P_{g\times}(k_{\parallel}, r_{\perp} = 0)$ may be negative for some values of k_{\parallel} . An auto-power spectrum must be positive definite, because the variance of Fourier modes can never be negative (for $r_{\perp} \neq 0$, $P_{g\times}(k_{\parallel}, r_{\perp})$ can be negative). Fortunately, this does not occur for the input model chosen here, but it may well occur with other distributions (see [13] for a discussion of the same problem in the context of non-Gaussian initial conditions).

2.3 Redshift evolution and non-parallel lines of sight

The power spectrum of δ_F is a function of redshift. The main evolution is in the amplitude of the power spectrum, but a more general evolution in the shape is likely to be present, particularly on small scales. To introduce the redshift evolution in our model, we generate the field δ_F for several discrete values of the redshift, obtaining a set of realizations $\delta_{Fi}(x_{\parallel}, x_{\perp})$, where the subindex i labels the redshift. Each of these realizations is generated with the same amplitudes and complex phases of the Fourier modes $\tilde{\delta}_g$, and varying only the amplitude of the power spectrum that is different due to the evolution with redshift. In other words, the realizations at different redshifts have all the same random elements and change only because of the variation in the power spectrum, so we can smoothly interpolate between them to obtain the generated field at any desired redshift.

The effect of the variation of the angular diameter distance and Hubble constant with redshift, and the fact that the lines of sight are not parallel, is included in the same way as the redshift evolution. The power spectrum can be expressed in terms of fixed angular and redshift separations at the discrete values of the redshift at which the multiple fields δ_{Fi} are generated.

The final field δ_F is obtained by linear interpolation of the multiple fields as the redshift varies along the lines of sight, introducing in this way the gradual evolution in the power spectrum amplitude, the Hubble constant and the angular diameter distance with redshift.

In this paper, the redshift values at which the fields δ_{Fi} are generated are $z = 1.96, 2.44, 2.91$, and 3.39 .

2.4 Input model for Ly α forest mocks used in this paper

The distribution and power spectrum of the transmitted flux fraction can be determined from observations and can also be computed in theory from hydrodynamic cosmological simulations of the intergalactic medium. As observational progress is made, mocks of Ly α forest surveys can be adjusted to reproduce as accurately as possible the observational determinations of the distribution and power spectrum of δ_F , which guarantees an accurate modeling of the measurement errors for any quantities. Here, we use the parameterized fitting formula introduced by [5] to fit the results of the power spectrum from several numerical simulations,

$$P_F(k, \mu_k) = b_{\delta}^2 (1 + \beta \mu_k^2)^2 P_L(k) D_F(k, \mu_k) , \quad (2.8)$$

where b_{δ} is the density bias parameter at $z = 2.25$, β is the redshift distortion parameter, $\mu_k = k_{\parallel}/k$, $P_L(k)$ is the linear matter power spectrum, and $D_F(k, \mu_k)$ is a non-linear term that approaches unity at small k . This form of P_F is the expected one at small k in linear theory, and provides a good fit to the observations reported in [8]. Note that we do not generate a density and a velocity field, but we directly generate the Ly α forest absorption field instead, with the redshift distortions being directly introduced in the input power spectrum model of equation (2.8), with the free parameter β that measures the strength of the redshift distortion.

We use the parameters given in the central model of [5], $b = -0.1315$ and $\beta = 1.58$ (the negative sign of b simply reflects the decrease of δ_F with gas density, and does not affect any equations in this paper because it always appears as b^2). Only the amplitude of the power spectrum is assumed to evolve with redshift, following a power-law:

$$P_F(k, \mu_k, z) = P_F(k, \mu_k, z = 2.25) \left(\frac{1+z}{1+2.25} \right)^{\alpha} . \quad (2.9)$$

We use the value $\alpha = 3.8$ in this paper, as suggested by the evolution of the one-dimensional $P(k)$ measured in [2].

For the probability distribution, we use a log-normal model for the optical depth τ ,

$$F = e^{-\tau} = \exp(-ae^{\gamma g}) , \quad (2.10)$$

where g is a Gaussian variable of unit dispersion, and a and γ are two free parameters determining the mean transmission \bar{F} and its variance.

In the future, a new distribution for F that more accurately matches the observed one should be used for the mocks, but the log-normal approximation suffices for the purpose of this paper of demonstrating the applications of Ly α forest mocks.

We assume a mean transmitted fraction that approximately matches the observations ([2]):

$$\ln \bar{F}(z) = \ln(0.8) \left(\frac{1+z}{3.25} \right)^{3.2} . \quad (2.11)$$

The values of a and γ at each redshift can be derived by requiring the mean value of F to match equation (2.11), and its dispersion to reproduce the value implied by the power spectrum P_F . The result for the parameters at the four redshifts we use are the following: $a = 0.065$ and $\gamma = 1.70$ at $z = 1.96$; $a = 0.141$ and $\gamma = 1.53$ at $z = 2.44$; $a = 0.275$ and $\gamma = 1.38$ at $z = 2.91$; and $a = 0.487$ and $\gamma = 1.24$ at $z = 3.39$.

3 Results

This section presents the results for the characteristic errors in the measurement of the correlation function, as an example of a simulated Ly α forest survey with similar characteristics as BOSS.

3.1 Model for the quasar survey

The first step to generate a mock Ly α forest survey is to generate the quasar sample. We randomly distribute quasars (with no clustering) over a circular area $A = 300 \text{ deg}^2$ and the redshift range $2.15 < z < 3.5$, following the quasar luminosity function measured in [14] up to a limiting magnitude of $g = 22$. We select only 75 % (independently of g magnitude and redshift) of the quasars in order to have a quasar number density closer to the one obtained in the BOSS survey ($\sim 15 - 17 \text{ deg}^{-2}$). The total number of quasars in the sample is $N_q \simeq 5000$. The code we use to generate the absorption fields with the method described in Section 2 was able to generate all the absorption spectra in one survey mock with a node with 8 CPU in a few hours.

The redshift distribution of the sources in a real survey usually differs substantially from that inferred from the model luminosity function, mainly because the target selection efficiency has a strong dependence on redshift. In particular, in the optical color selection used by SDSS, quasars at $z \sim 2.7$ overlap the stellar locus and are confused with stars, making them harder to select. There is also a change in efficiency as a function of the foreground stellar density and dust absorption. We do not include these effects here. If anything, these effects should reduce the errors of measuring the Ly α correlation because they should cause an increased overlap of the Ly α spectra redshift range and an increased number of quasar pairs at small separations, for fixed mean quasar density.

After having constructed the spectra of the transmitted fraction F as described in the previous section, we generate a realistic observed quasar spectrum that includes the spectral resolution and noise approximately matching those in the BOSS survey, following these steps:

- A new set of pixels for a mock of the physical spectrum in units of flux is constructed, covering the whole, fixed wavelength range $3600 \text{ \AA} < \lambda < 9000 \text{ \AA}$, with pixels of constant wavelength width $\Delta\lambda = 1 \text{ \AA}$. The width of these pixels in comoving separation is therefore changing along the spectrum.

For each quasar, we compute the mean value of the pixel width (R_w) and the mean value of the Point Spread Function (R_p) in comoving separation, over the region that is used for measuring the Ly α forest correlation function, $1041 \text{ \AA} < \lambda < 1185 \text{ \AA}$ in the rest frame. We then convolve our spectrum of δ_F in the original pixels of constant comoving length with the Point Spread Function that results from the convolution of a Gaussian spectral resolution and the pixel width in the final wavelength bins:

$$\delta_F(x) = \frac{1}{2\pi} \int dk e^{ikx} \tilde{\delta}_F(k) \exp\left[-\frac{k^2 R_p^2}{2}\right] \left[\frac{\sin(k R_w/2)}{k R_w/2}\right]^2. \quad (3.1)$$

The values of R_p , R_w depend on the quasar redshift, with typical values being in the range $0.6 - 0.8 h^{-1} \text{ Mpc}$. We note that the wavelength dependence of the spectral resolution and the pixel width in the BOSS spectrograph are actually quite complex, and they should be carefully treated if one is interested in small-scale correlations.

- Each pixel in the spectrum with constant wavelength bins is assigned the value of F in the nearest bin of the spectrum with pixels of constant comoving width. We set $F = 1$ for wavelengths outside the Ly α forest range.
- We multiply the spectrum of F by the continuum for each quasar, using the mean rest-frame spectra obtained in [15]. A spectrum of physical flux, $f(\lambda)$, is obtained after normalizing to match the g magnitude of the quasar.
- The expected noise variance for the case of the BOSS spectrograph with an exposure time of 1 hour is computed at each pixel using the expression

$$\sigma_N^2(\lambda) = A + B(\lambda) [f(\lambda) + s(\lambda)] \Delta\lambda, \quad (3.2)$$

where $s(\lambda)$ is a typical sky flux in BOSS, A is the read-out noise and $B(\lambda)$ is related to the BOSS throughput. These functions have been estimated using BOSS survey code [16].

- We add a Gaussian random variable with variance σ_N^2 to the flux $f(\lambda)$ at each pixel, and divide the resulting flux by the continuum to obtain a new spectrum of transmitted fraction F (which is no longer restricted to the range $0 < F < 1$ because of the noise that has been added).

The detailed properties of the noise in the real survey are more complicated, but this simple procedure allows us to approximately study the effect of noise on the correlation function measurement.

An example of mock spectra with continuum and noise added is shown in Figure 1.

We have generated 50 realizations of this mock survey to obtain the results that are presented next.

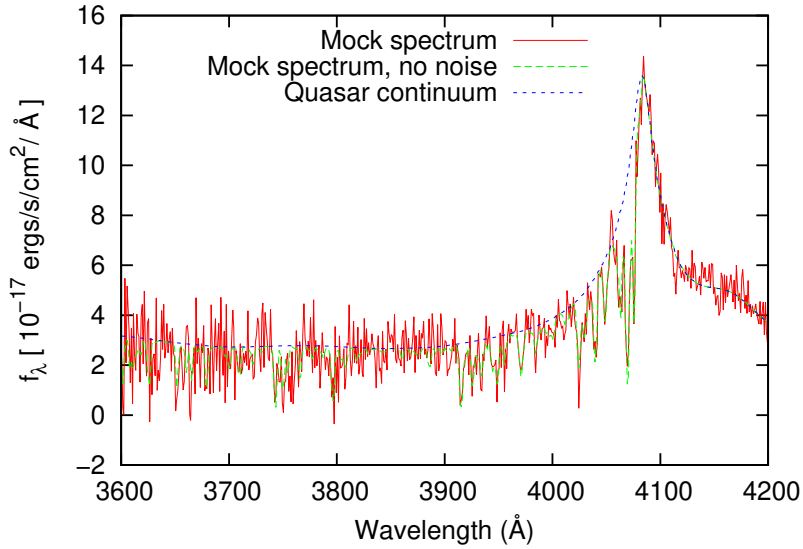


Figure 1. Mock quasar spectrum (*solid red*), without noise (*dashed green*) and without Ly α absorption (*dashed blue*).

3.2 Measurement of the Correlation Function

We estimate the value of the correlation function as the weighted average of the product of the δ_F variable in all pixel pairs that have a redshift space separation r , angle cosine μ and mean redshift z , which are within a certain bin of width Δr , $\Delta \mu$ and Δz , which we designate as A :

$$\hat{\xi}_A = \frac{\sum_{i,j \in A} w_i w_j \delta_{Fi} \delta_{Fj}}{\sum_{i,j \in A} w_i w_j}. \quad (3.3)$$

The weights w_i for each pixel are to be chosen to minimize the error of the correlation function estimator, although special care needs to be taken on any possible bias that they may introduce. Our first choice for the weights was to set them equal to the total inverse variance in each pixel. The total variance is equal to the sum of the intrinsic Ly α forest fluctuations, $\sigma_F^2(z) = \langle \delta_F^2 \rangle$, and the variance caused by the instrumental noise, $\sigma_N^2(\lambda) / [\bar{F}(z)C(\lambda)]^2$, so the weights are

$$w_i = \sigma_i^{-2} = \left[\sigma_F^2(z_i) + \frac{\sigma_N^2(\lambda_i)}{\{\bar{F}(z_i) C(\lambda_i)\}^2} \right]^{-1}. \quad (3.4)$$

These are the same weights that were adopted in [8]. The effect of the intrinsic variance correlation in neighboring pixels is ignored, as was done in [8], since this is not expected to have any effects on large scales. Note that the noise variance in equation 3.2 applies to the flux variable $f(\lambda) = \bar{F}[1 + \delta_F(\lambda)]C(\lambda)$. The corresponding contribution to the variance of δ_F in equation 3.4 is obtained by dividing by $[\bar{F}(z)C(\lambda)]^2$.

The correlation function is estimated first on a large number of small enough bins for the final result to have converged to the correct value, using 150 bins in r up to $r = 150 h^{-1}$ Mpc, 20 bins in μ and 20 bins in z , all of them linearly spaced. Then, for the purpose of plotting the results, the correlation function is averaged over all redshifts and compressed into broader bins of 10 Mpc/ h in r , and three bins in μ . This average over the small bins into the broader

bins is done using the combined weights of each of the small bins, in the same way for the theoretical value of the correlation function and its estimate obtained in each mock. The results are plotted in the left panel of Figure 2, where the average estimate from the 50 mocks is shown as the points with errorbars, and the theoretical value from the model power spectrum used to generate the mocks is shown as the curves.

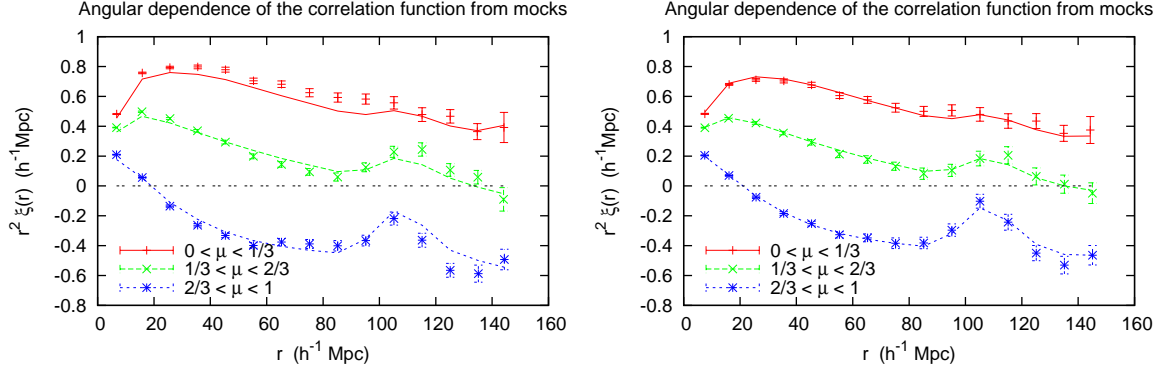


Figure 2. Correlation function obtained from the average of 50 mocks of our survey model (*points*), as a function of r in three different bins in $\mu = \cos(\theta)$, compared to the input model (*lines*). The errorbars are computed for the average of 50 mocks, from the dispersion between them. *Left panel:* Pixel weights from equation 3.4, which introduce a bias owing to their dependence on the measured flux. *Right panel:* Pixel weights from equation 3.5, which are unbiased.

The errorbars reflect the expected errors for the average of 50 mocks, and have been computed from the dispersion between the 50 mocks. Therefore, the true errors of one of our realizations of a survey with an area of 300 square degrees are larger by a factor $\sqrt{50 - 1} = 7$. This neglects the edge effects of the survey (the fact that fewer pairs of quasars are found for quasars near the edge of the survey area), which are small. For reference, the BOSS survey is expected to cover an area of about 30 times that of one of our mocks, with about the same quasar density, so the errors for the final BOSS results should be about $\sqrt{5/3}$ larger than in Figure 2.

As we can see in the left panel of Figure 2, there is a disagreement between the input theory and the measured correlation function that is clearly above the errors. This disagreement is due to the bias of the weights in equation 3.4: the weights are systematically smaller for pixels with a smaller value of δ_F . This causes the bias in the estimator for the correlation function. To remove this bias, equation 3.4 can be modified to the following form, in which the weight is set equal to its value for $\delta_F = 0$ and does not depend on the measured flux:

$$w'_i = \left\{ \sigma_F^2(z_i) + \frac{A + B(\lambda_i) \Delta \lambda [\bar{F}(z_i) C(\lambda_i) + s(\lambda_i)]}{[\bar{F}(z_i) C(\lambda_i)]^2} \right\}^{-1}. \quad (3.5)$$

The results obtained using the weights w'_i are shown in the right panel of Figure 2, showing a complete absence of any bias. This example illustrates that particular care needs to be taken in the future in the choice of weights to obtain unbiased estimates of the correlation function:

a better estimator than the one used in [8] will be required for a proper interpretation of the measurements with the final BOSS data set.

According to this prediction, the amplitude of the BAO peak should be detectable at the $\sim 5 - \sigma$ level in bins of $10h^{-1}$ Mpc in r in the correlation function if all the data obtained in BOSS is as expected, in agreement with previous authors.

3.3 Variations in the Survey Strategy

An application of the mock Ly α forest surveys is to calculate the precision achieved in the measurement of the correlation function on large scales as a function of any survey properties in order to optimize the design of the survey. This study may often be done using a Fisher matrix approach without the need to generate survey realizations, but using the mocks presented here allows one to include any possible systematic effects in a more complete way.

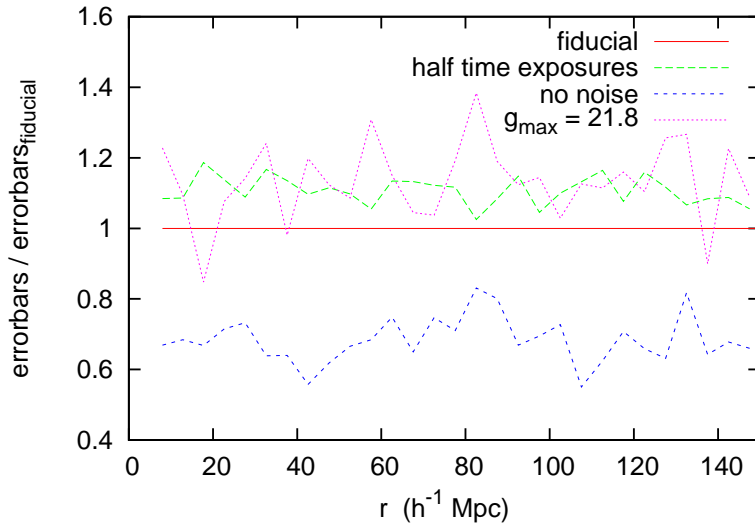


Figure 3. Fractional change in the errorbars of the correlation function, for each radial bin, with respect to the fiducial survey, when varying survey parameters. The dashed green line assumes that only half as many exposures are obtained (i.e., the signal-to-noise is reduced by a factor $\sqrt{2}$), and the dotted pink line shows the result of eliminating the faintest 16% of the quasars with $21.8 < g < 22$. The dotted blue line is for the case with no observational noise.

Here we study the change in the errorbars of the correlation function when we vary either the exposure time or the number of observed quasars within a fixed area.

We note that the variation of these errorbars with the area of the survey, if we keep the quasar density fixed, is basically proportional to the inverse square root of the area, apart from the presence of edge effects, which are already small at the BAO scale for our fiducial survey with an area of 300 deg^2 .

Figure 3 shows that the fiducial survey has errors that are reduced by $\sim 30 \%$ if the observational noise (both photon and read-out noise in the detectors) were entirely eliminated. In other words, the errors arising from observational noise and from the intrinsic sampling variance in the Ly α forest are comparable in our fiducial survey. The best strategy to reduce the sampling variance is to aim for the largest possible survey area. Increasing the source density is more difficult because one has to search for fainter quasars, which are harder to

identify and have larger observational noise for a fixed exposure. The curves in Figure 3 show that reducing the number of exposures by a factor of 2 degrades the error bars by the same amount (10 to 15%) as eliminating the faintest 16% of the quasars, in the magnitude range $21.8 < g < 22$. Therefore, this shows that maximizing the number of quasars that are observed is the best survey strategy, even near the magnitude limit of the BOSS spectroscopic quasar survey (see [17]), and even if this is done at the cost of some reduction in the exposure time.

A simple Fisher matrix approach was used in [7] to study the best survey strategy to measure the angular diameter distance $D_A(z)$ and the Hubble parameter $H(z)$ from the BAO wiggles in the power spectrum. In their Figure 1, these authors show that when the survey limiting magnitude is reduced from $g = 22$ to $g = 21.8$, the fractional error on the angular distance $D_A(z)$ increases by $\sim 20\%$ and the Hubble parameter $H(z)$ increases by $\sim 10\%$, in agreement with the 10 – 15% increase of the errorbars that we find (the S/N used for their figure is higher than in our mocks, so their improvement for a fainter limiting magnitude should be slightly higher than ours). In their Figure 5, [7] show that the fractional error on both scales increases by $\sim 10\%$ if the $(S/N)^2$ is reduced by a factor of 2 (equivalent to reducing the number of exposures by a factor 2), also in agreement with the 10 – 15% increment of the errorbars found in the analysis of our mocks. Similar results were obtained by [18]. Our results therefore confirm these earlier studies, where we have now included various effects in greater detail, such as the redshift evolution, the expected length of the observable spectra and their degree of overlap (these are typically included in Fisher matrix calculations in a somewhat abstract, averaged way).

Our method is highly flexible to allow for a rapid computation of the best strategy for survey optimization, including any systematic effects that one may consider and include in the mocks in a realistic way. The mocks described here were already used to make a preliminary study of the systematic effects of continuum fitting errors, spectroscopic noise, metal absorption lines and high column density systems for the first measurements with BOSS presented in [8].

3.4 Comparison with Gaussian field errorbars

The forecasts for the accuracy of correlation function measurements with the Fisher matrix approach in [7] and [18] assumed that the field can be modeled as a Gaussian variable. We can test that this hypothesis does not indeed alter the result by generating mocks of a Gaussian field and of a field with the lognormal distribution of equation 2.10, with the same power spectrum and generated with the same random numbers.

In Figure 4 we show that the errorbars in the measurement of the angular-averaged correlation function of a Gaussian mock survey are nearly identical to the errorbars of a lognormal mock survey. This confirms the expected result that the errorbars are not sensitive to the 1-point function and are determined solely by the power spectrum (this does not, however, test the importance of longer range gravitational non-linearity [19], although we do not expect this to be important on large scales either).

4 Conclusions

The method described here is able to create mock correlated spectra of the Ly α forest surveys mimicking the observed properties of real surveys. Two free functions can be introduced as input to the mocks, fixing the one-point distribution and two-point correlation function of

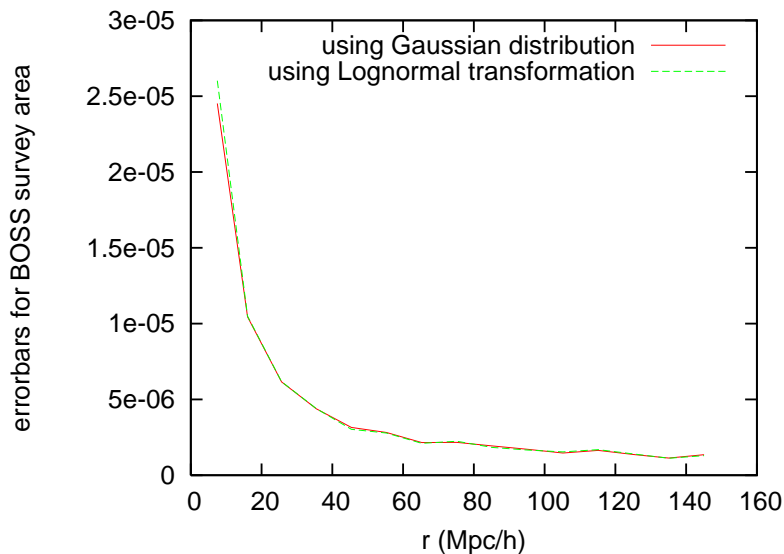


Figure 4. Comparison of the errorbars in the angular averaged correlation function expected for a survey similar to BOSS, compared to mocks where the field has the same power spectrum but a Gaussian distribution.

the field δ_F , which can be made to evolve with redshift. The higher order n -point functions that are not reproduced are not expected to significantly affect the measurement errors of 2-point statistics on the large scales of interest.

This paper presents only a simple example of the application of these mocks to a survey with similar characteristics as BOSS. The technique has already been used in the first analysis of BOSS data in [8]. In the future, we plan to improve our methodology to apply it to a number of sources as large as the entire BOSS survey, and to include all the observational effects in increasing detail. For example, one of the main applications of these mocks is to accurately model the effect of high column density systems and metal-line absorption systems on the measurement of the Ly α forest correlation, which will be described in [10].

Recently, [20] and [21] have also presented methods for generating mock surveys of Lyman alpha absorption. Both of these studies generate Gaussian fields in a 3D grid for the density and the velocity field, and compute the transmitted flux using a lognormal transformation. As mentioned in our Section 2, these methods face computational challenges owing to the large amount of memory that is required, which limits their study to small volumes (area of 79 deg^2 in [20]) or poor resolution (cell size of $3.2 h^{-1} \text{ Mpc/h}$ in [21]). Furthermore, they cannot easily produce large numbers of realizations of a survey with the observed range of redshifts that are truly independent of each other, because of the difficulty in running many independent 3D simulations and storing their outputs.

An important difficulty of our method is still the memory needed to store the covariance matrices of each k -mode, because their size grows with the square of the number of simulated lines of sight. This limits the number of lines of sight to $\sim 10^4$ when running the code in a 24-CPU node with 32 Gb of shared memory (the CPU time used is ~ 100 hours). We are currently working on an improved version of the code that will be able to avoid this limitation by using MPI and sparse matrix algorithms.

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